Fermi National Accelerator Laboratory

FN-487
[SSC-N-517]
{LBL-25385}

Beam Impedances of Position Monitors, Bellows, and Abort Kicker*

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May 1988

*Submitted to the Proceedings of the Workshop on RHIC Performance, Brookhaven National Laboratory, Upton, Long Island, New York, March 21-26, 1988

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

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[†]Work supported by U.S. Dept. of Energy under Contract No. DE-AC03-76SF00098.
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I. INTRODUCTION

The miscellaneous components of an accelerator may contribute a substantial or even dominant part of the interaction between beam and surroundings. We have estimated the beam impedances of a few of these components. When needed, we have added our own conceptions to the descriptions available at the Workshop on the RHIC Performance in order to make definite the calculations of impedance. These assumed parameters, while not unique, hopefully illustrate feasible and typical designs.

II. BEAM POSITION MONITORS

The beam position monitors in the RHIC main ring are of stripline split cylinder type. Each stripline is of length ℓ, subtends an angle ϕ_0 at the beam axis, and is terminated at both ends by impedances Z_s, the characteristic impedance between the stripline and the beam pipe. Below cutoff frequency, the longitudinal coupled impedance for one monitor system consisting of two striplines is[1,2]

$$Z_{\|}(\omega) = 2Z_s\left(\frac{\phi_0}{2\pi}\right)^2\left(\sin^2\frac{\omega\ell}{c} + j\sin\frac{\omega\ell}{c}\cos\frac{\omega\ell}{c}\right) , \tag{2.1}$$

where $\omega/2\pi$ is the frequency under consideration. The coupling impedance in the transverse direction between the striplines is[2]

$$Z_{\perp}(\omega) = \frac{c}{\omega b^2}\left(\frac{4}{\phi_0}\right)^2\sin^2\frac{\phi_0}{2}Z_{\|} , \tag{2.2}$$

where b is the radius of the beam pipe, c is the velocity of light, and $Z_{\|}$ is given by Eq. (2.1). The coupling impedance in the other transverse direction vanishes in this model. However, a contribution may arise at higher frequencies as a result of resonances in the realistic situation.

In RHIC, $Z_s = 50\ \Omega$, $\ell = 20$ cm, $b = 3.645$ cm, and $\phi_0 \sim \pi/2$. For frequencies

$$\frac{\omega}{2\pi} \ll \frac{c}{2\pi\ell} = 0.24\ \text{GHz} , \tag{2.3}$$

Eq. (2.1) can be simplified to

$$\frac{Z_{\|}}{n} = jZ_s\frac{2\ell}{R}\left(\frac{\phi_0}{2\pi}\right)^2 . \tag{2.4}$$

Here $R = 610.18$ m is the mean radius of each RHIC ring, and $n = \omega/\omega_0$, where $\omega_0/2\pi$ is the revolution frequency. At higher frequencies, $Z_{\|}$ alternates between inductive and capacitive and there is a contribution of the real part too. However, there are no resonances.

There is a total of 250 beam position monitors in each ring. Therefore, the total contributions are

$$\frac{Z_{\|}}{n} = j0.512\ \Omega\ , \tag{2.5}$$

and

$$Z_{\perp} = j0.381\ \mathrm{M\Omega/m} \tag{2.6}$$

in each of the two transverse directions.

III. BELLOWS

The RHIC bellows are of the inner type. The longitudinal and transverse coupling impedances can be derived by running TBCI and taking Fourier transforms.[3] The general behavior corresponds to two broad resonances above cutoff frequency, as shown in Fig. 1. Analytic results can be inferred[4] by describing these broad resonances with the formulas

$$Z_{\|}(\omega) = \frac{R_{\|}}{1 - jQ\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)}\ , \tag{3.1}$$

and

$$Z_{\perp}(\omega) = \frac{\omega}{\omega_r}\frac{R_{\perp}}{1 - jQ\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)}\ , \tag{3.2}$$

where the positions of the resonances, ω_r, are roughly the same, the quality factor Q is ~ 3 to 5, and $R_{\|}$ and $R_{\perp}$ are the respective shunt impedances. The next resonance will be at $\sim 3\omega_r$; it is heavily damped, and can therefore be neglected.

If the beam pipe has a radius b and each corrugation of the bellows has a depth Δ, we can imagine the resonance is formed inside the corrugation with a wavelength $2\pi c/\omega_r \approx 4\Delta$. Because the frequency $\omega_r/2\pi$ is above cutoff (because $\Delta < b$ in most cases), the resonant fields will leak out of the corrugation, cling to its opening, and effectively increase the corrugation depth. Also, with the presence of many adjacent corrugations, closely spaced, the fields will link across several corrugations resulting in further lengthening of the effective corrugation depth. An examination of bellows of different sizes gives, for corrugations with $\Delta/b < 0.5$ and $\Delta > 0.25$ cm, an empirical formula

$$\frac{\omega_r\Delta}{c} = 1.37\left(\frac{\Delta}{b}\right)^{0.052}\ , \tag{3.3}$$

Since the exponent is small, Eq. (3.3) can be interpreted as the lowering of $\omega_r\Delta/c$ from $\pi/2$ to 1.37 due to the apparent elongation of Δ by the leaking fields.

The ratios of shunt impedances to quality factors are related to the low-frequency behavior of the impedances. From Eqs. (3.1) and (3.2) at zero frequency, we get

$$\frac{\mathcal{I}m\, Z_\parallel}{n} = \frac{R_\parallel}{n_r Q} \qquad \text{and} \qquad \mathcal{I}m\, Z_\perp = \frac{R_\perp}{Q}\,, \tag{3.4}$$

where $\omega_r = n_r\omega_0$. On the other hand, from the low-frequency magnetic field trapped inside a narrow cavity, we obtain[5]

$$\frac{\mathcal{I}m\, Z_\parallel}{\omega} = \frac{gZ_0}{\pi c}\ln S \qquad \text{and} \qquad \mathcal{I}m\, Z_\perp = \frac{2gZ_0}{\pi b^2}\frac{S^2-1}{S^2+1}\,, \tag{3.5}$$

where $Z_0 = 377\ \Omega$, g is the gap width of one corrugation, and $S = 1+\Delta/b$. The impedance for many corrugations is roughly the impedance of one corrugation multiplied by the number of corrugations.

For the RHIC main ring, there are three possible options, of different depths Δ and lengths ℓ, for roughly 500 bellows. The total widths of the corrugations will be taken as $\ell/2$ for each bellows. These different options and their corresponding impedances are listed in Table I.

Bellows	Depth Δ	Length ℓ	Resonant Freq	$\dfrac{\mathcal{I}m\, Z_\parallel}{n} = \dfrac{R_\parallel}{n_r Q}$	$\mathcal{I}m\, Z_\perp = \dfrac{R_\perp}{Q}$
	(mm)	(cm)	(GHz)	(Ω)	(MΩ/m)
Option #1	4	10.1	14.6	0.517	0.473
Option #2	6	9.0	9.93	0.674	0.615
Formed	9	12.9	6.76	1.400	1.27

Table I: Impedances for different options of bellows.

The cutoff frequency for a pipe radius of $b = 3.645$ cm is 3.15 GHz. We see from Column 4 that the broad resonance for each bellows option is situated well above cutoff. The 5th column gives $\mathcal{I}m\, Z_\parallel/n$ at zero frequency and $R_\parallel/n_rQ$ at the peak of the resonance for a total system of 500 bellows, while the transverse counterparts $\mathcal{I}m\, Z_\perp$ at zero frequency and $R_\perp/Q$ at the resonant peak are given in the 6th column. The "formed" option gives the highest impedances.

Parasitic heat loss due to the bellows is given by[4,6]

$$P = e^2 Z^2 N^2 M k_{\|} \frac{\omega_0}{2\pi} , \tag{3.6}$$

where M is the number of bunches each containing N particles of charge eZ,

$$k_{\|} = \frac{1}{\pi} \int_0^\infty d\omega e^{-(\omega\sigma_\ell/c)^2} \mathcal{R}e\, Z_{\|} \tag{3.7}$$

is the energy loss factor, and $Z_{\|}$ is the longitudinal coupling impedance for all the bellows corrugations in one ring. The rms bunch length is $8.6/\sqrt{6} = 3.51$ ns or $\sigma_\ell = 105$ cm. Thus $\alpha = \omega_r \sigma_\ell / c = 322$, 219, and 149 respectively for the three bellows options. Since $\alpha \gg 1$, using Eq. (3.1), the energy loss factor can be approximated by

$$k_{\|} = \frac{R_{\|}\omega_r}{4\sqrt{\pi} Q^2 \alpha^3} . \tag{3.8}$$

There are $M = 57$ bunches per beam, each containing 1×10^{11} protons of unit charge or 1×10^9 gold ions of charge $Z = 79$. The power losses to the bellows per beam are computed for the three bellows options and are listed in the second and third columns of Table II. We see that the parasitic heat loss to the bellows is not big. This

	Low rf		High rf
	Proton (watts)	Gold (watts)	Gold (watts)
Option #1	0.043/Q	0.027/Q	9.2/Q
Option #2	0.082/Q	0.051/Q	18/Q
Formed	0.25/Q	0.16/Q	54/Q

Table II: Parasitic heating to the bellows per beam.

is mainly due to the long bunch length and the small number of bunches.

There is a suggestion to run RHIC at a high rf of 214 MHz (harmonic number 8 times bigger) at the high energy end. There, the bunch length for gold ions is $\sigma_\ell \approx 15$ cm. Then $\alpha = 45.9$, 31.2, and 21.2 respectively for the three bellows options. Since $\alpha \gg 1$, Eq. (3.8) can still be used. In other words, the loss factor $k_{\|}$ scales as

σ_ℓ^{-3}. Assuming that the number of bunches will remain at $M = 57$, the power losses to the bellows per beam are shown in the last column of Table II. They are very much larger.

IV. ABORT KICKER

The abort kicker is a large ferrite magnet that may introduce substantial beam impedances at low frequencies. A conductive liner may be provided to reduce coupling at high frequencies. Also, to reduce magnetic flux that could encircle the beam entirely in the ferrite, the yoke should be divided on the vertical midplane with a copper sheet, making essentially two facing C-magnets. It is assumed that the kicker will be in two sections, each built as a traveling-wave device with velocity v and line impedance Z_s. Assumed geometry and parameters are shown below. (See Fig. 2, where the kicker is shown without a liner.)

$$\begin{aligned}
\text{2 magnets, each of length} \quad & \ell &=&\ 6 \text{ m} \\
\text{opening height} \quad & 2a &=&\ 40 \text{ mm} \\
\text{opening width} \quad & 2b &=&\ 80 \text{ mm} \\
\text{possible orbit offset} \quad & x &=&\ 3 \text{ mm} \\
\text{thickness of copper sheet} \quad & w &=&\ 5 \text{ mm} \\
\text{line impedance} \quad & Z_s &=&\ 15\ \Omega \\
\text{traveling-wave velocity} \quad & v &=&\ 0.04c \\
\text{rotation frequency} \quad & \omega_0 &=&\ 2\pi\, 78 \times 10^3 \text{ Hz}
\end{aligned}$$

Even with the copper barriers, flux may leak around their edges. An estimate of the inductance of the two yokes from this leakage is

$$L \approx 2\frac{\mu_0 \ell}{2\pi} \ln \frac{\pi a}{2w} \ . \tag{4.1}$$

This contributes to the imaginary part of $Z_\parallel$, for the assumed dimensions

$$\frac{\mathcal{I}m\, Z_\parallel}{n} = \omega_0 L = 2.162 \text{ ohm} \ . \tag{4.2}$$

Coupling to the power supply and terminating resistors introduces longitudinal impedance, unless the orbit is horizontally centered in the aperture. This impedance, at frequency $\omega/2\pi$, is[7,8]

$$\mathcal{R}e\, Z_\parallel = 2\frac{1}{8Z_s}\left(\frac{\omega\mu_0 \ell x}{a}\frac{\sin k\ell/2}{k\ell/2}\right)^2 \qquad k = \omega/v \ , \tag{4.3}$$

or

$$
\begin{aligned}
\frac{\mathcal{R}e\, Z_{\|}}{n} &= \frac{\ell v \omega_0}{2Z_s}\left(\frac{\mu_0 x}{a}\right)^2 \frac{\sin^2 k\ell/2}{k\ell/2} \\
&= 0.0418\,\frac{\sin^2 k\ell/2}{k\ell/2}\ \text{ohm}\ , \qquad (4.4)\\
\frac{\mathcal{I}m\, Z_{\|}}{n} &= \frac{\mathcal{R}e\, Z_{\|}}{n}\,\frac{k\ell - \sin k\ell}{2\sin^2 k\ell/2} \\
&= 0.0418\left(1 - \frac{\sin k\ell}{k\ell}\right)\ \text{ohm}\ . \qquad (4.5)
\end{aligned}
$$

The shielding effect of the conductive liner is limited by the amount of delay and distortion in the kicker field that is tolerable. That delay Δt, relative to the risetime τ is approximately

$$\frac{\Delta t}{\tau} = \frac{\mu_0 b}{\mathcal{R}_s \tau}\frac{L'}{L}\ , \qquad (4.6)$$

where L is the magnetic inductance, L' is the leakage inductance between liner and winding, $\mathcal{R}_s$ is the surface resistivity of the shell of radius b, and τ is taken as about 1 μsec. If $L' = L/10$, perhaps we could tolerate

$$\frac{\mu_0 b}{\mathcal{R}_s \tau} = 0.5\ , \qquad (4.7)$$

which gives for $\mathcal{R}_s$ the value of 0.1 Ω/square. The contribution, then, of this thin resistive layer to the beam impedance at low frequency is

$$Z_{\|} \approx 2\mathcal{R}_s \frac{\ell}{2\pi a} = 9.6\ \Omega\ , \qquad (4.8)$$

or

$$\frac{Z_{\|}(f)}{n} = 0.75 \times 10^6/f\ \Omega\ , \qquad (4.9)$$

and

$$Z_{\perp}(f) = \frac{2c}{\omega b^2} Z_{\|} = 0.57 \times 10^{12}/f\ \Omega/\text{m}\ , \qquad (4.10)$$

where f in Hz is the frequency under consideration.

These liner impedances combine in parallel with those of the kicker magnet. Therefore, the reactive impedance of the yoke will dominate the total longitudinal coupling up to about 1 MHz, beyond which the liner impedance controls. The coupling to the external circuit is small relative to these. The longitudinal impedances are sketched in Fig. 3.

To calculate the transverse coupling to the external circuit, use[8]

$$\mathcal{R}e\, Z_\perp = 2\frac{Z_0\ell}{4abk\ell}(1-\cos k\ell) = 1.414\left(\frac{1-\cos k\ell}{k\ell}\right)\ \mathrm{M}\Omega/\mathrm{m}\ , \tag{4.11}$$

$$\mathcal{I}m\, Z_\perp = 2\frac{Z_0\ell}{4ab}\left(1-\frac{\sin k\ell}{k\ell}\right) = 1.414\left(1-\frac{\sin k\ell}{k\ell}\right)\ \mathrm{M}\Omega/\mathrm{m}\ . \tag{4.12}$$

These impedances, combined with that of the liner, are shown in Fig. 4. Here, the liner controls the impedance from about 0.5 MHz upward.

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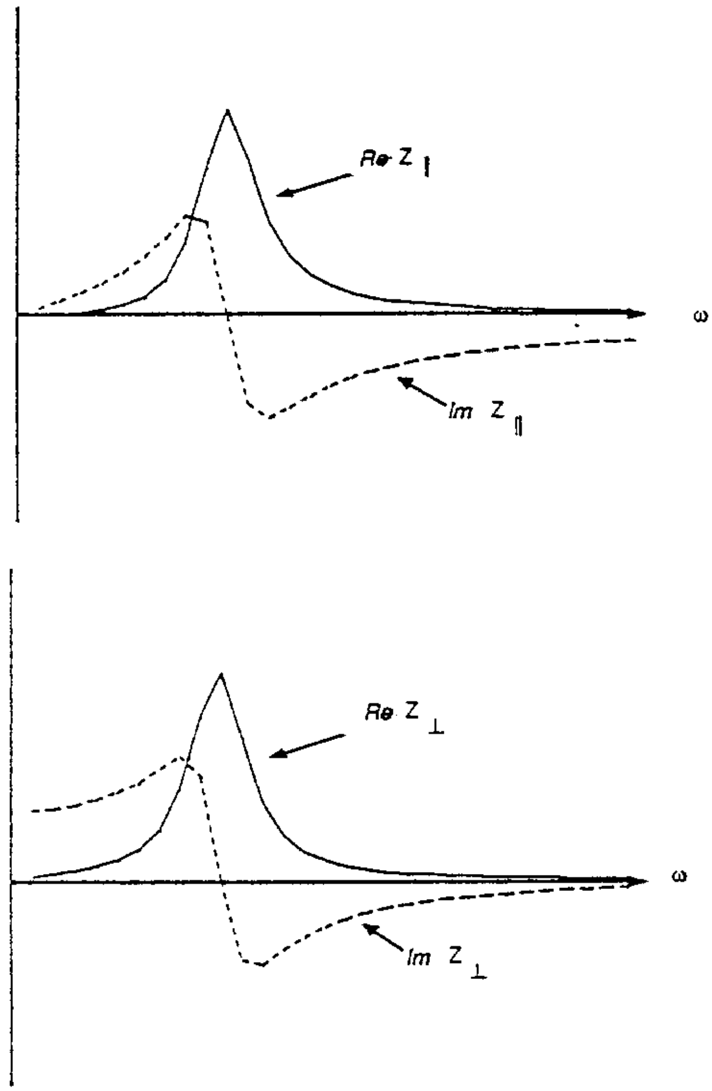

Fig. 1 Schematic plots of longitudinal and transverse bellows impedance.

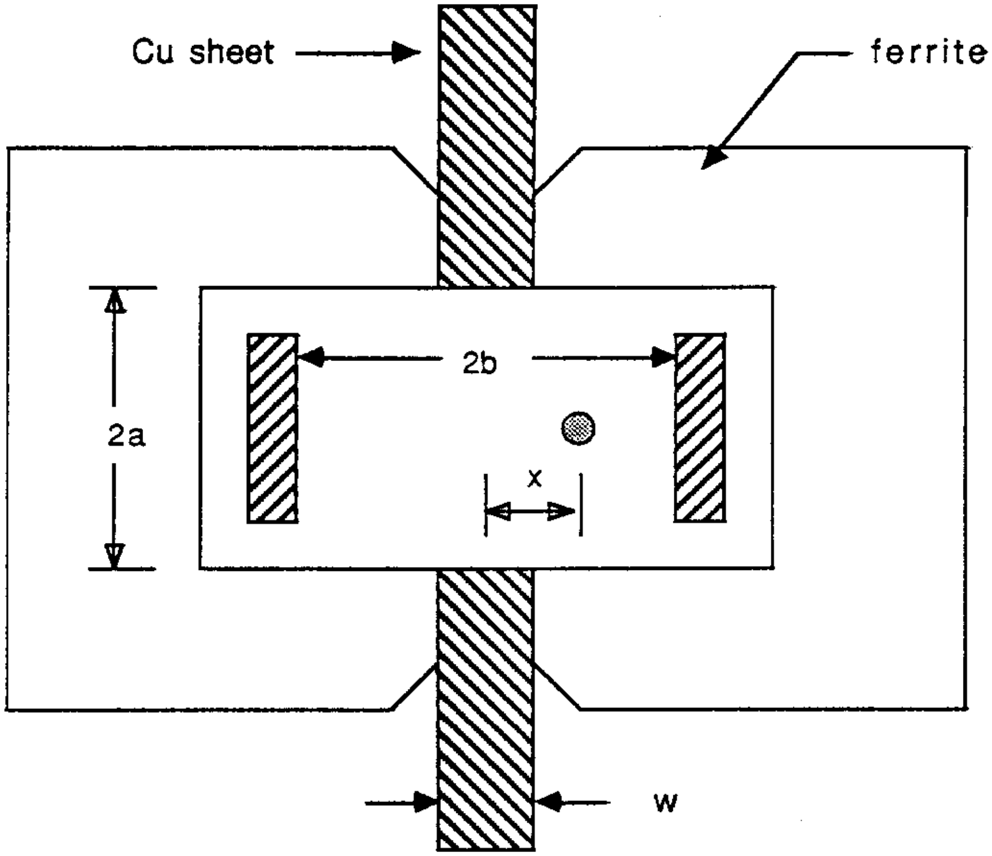

Fig. 2 Abort kicker schematic.

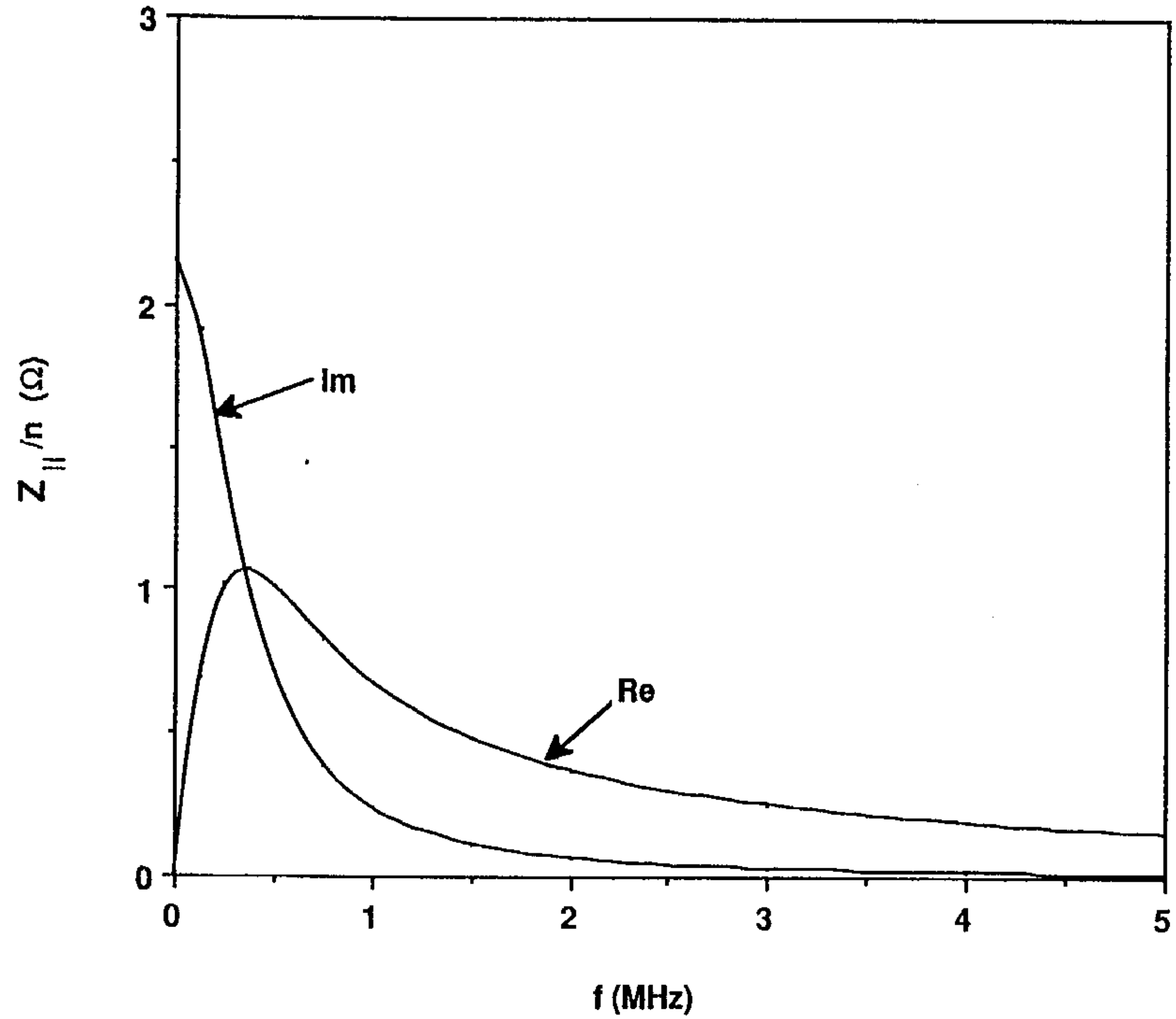

Fig. 3 Longitudinal Impedance of Abort Kicker Magnet

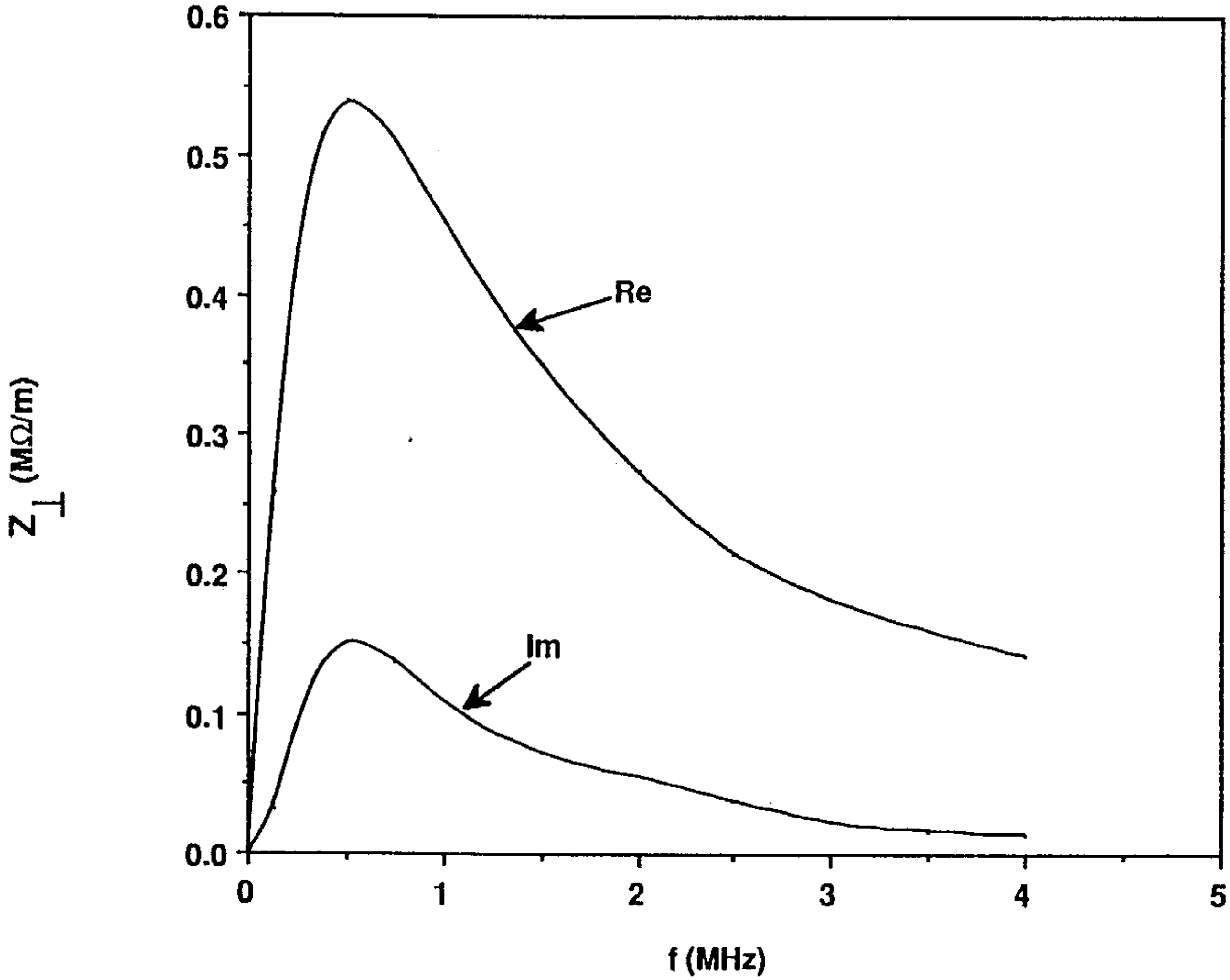

Fig. 4   Transverse Impedance of Abort Kicker Magnet